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Design and Evaluation of Wireless DYU Air Box for Environment-Monitoring IoT System on Da-Yeh University Campus

Lun-Min Shih, Huan-Liang Tsai * and Cheng-Yu Tsai

Department of Computer Science and Information Engineering, Da-Yeh University, Changhua 515006, Taiwan; lmshih@mail.dyu.edu.tw (L.-M.S.); r1106001@cloud.dyu.edu.tw (C.-Y.T.)
* Correspondence: michael@mail.dyu.edu.tw; Tel.: +886-932-162223

Abstract: This paper presents an original wireless DYU Air Box of an environment-monitoring IoT (EMIoT) system on a campus to offer information on environmental conditions through the public ThingSpeak IoT platform for stakeholders including all the students and employees on the Da-Yeh University (DYU) campus in Taiwan. Firstly, the proposed wireless heterogeneous multi-sensor module aggregates BME680, SCD30, PMS7003, and BH1750 sensors with a TTGO ESP32 Wi-Fi device based on the I^2C and UART interface standards of series communication. Through the DYU-802.1X Wi-Fi network with the WPA2 Enterprise security directly, the wireless multi-sensor monitoring module further forwards the observation data of environmental conditions on campus via the DYU-802.1X Wi-Fi network to the public ThingSpeak IoT platform, which is a cloud service platform to aggregate, visualize, and analyze live sensing data of air quality index (AQI), concentrations of $PM_{1.0/2.5}$ and CO_2, brightness, ambient temperature, and relative humidity (RH). The results illustrate the proposed DYU Air Box for monitoring the indoor environmental conditions on campus and validate them with sufficient accuracy and confidence with commercialized measurement instruments. In this work, the wireless smart environment-monitoring IoT system features monitoring and automatic alarm functions for monitoring AQI, CO_2, and PM concentrations, as well as ambient illumination, temperature, and RH parameters and collaboration and interoperability through the Enterprise Intranet. All the organizational stakeholders interested in the environmental conditions of the DYU campus can openly access the information according to their interests. In the upcoming future, the information of the environmental conditions in the DYU campus will be developed to be simultaneously accessed by all the stakeholders through both the public ThingSpeak IoT platform and the private EMIoT system.

Keywords: wireless DYU Air Box; ThingSpeak IoT; environment-monitoring IoT (EMIoT); 802.1X Wi-Fi network

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1. Introduction

As highlighted in the Sustainable Development Goals (SDGs) by the United Nations General Assembly (UNGA) in 2015 (United Nations) [1,2], education plays a fundamental and indispensable role in directly contributing to the goals of poverty reduction and inequalities, improvement of health and nutrition, facilitation of economic growth and labor market opportunities, and cost-effective achievement of all the sustainable development perspectives. On the other hand, recently, environmental, social, and corporate governance (ESG) has been gaining much attention from all organizational stakeholders including employees, customers, suppliers, and financiers. Higher educational institutions (HEIs), especially colleges and universities, are expected to take proactive strategies and actions in sustainable development ESG and are responsible to the students, faculty, and staff on campus, as well as the alumni and the other stakeholders, to ensure their investments in comply with the corresponding multi-faceted values. In general, the infrastructure of university campuses is built at a relatively high population density. Therefore, environmental pollution is an important issue with short- and long-term effects on the surrounding communities and society. This means monitoring and assessment of environmental impacts are crucial to the sustainable well-being and health of university communities. Moreover, the important perspectives of the sustainable development of policies and implementation of activities for university organizations to minimize negative environmental effects are taken into consideration to cost-effectively implement organizational social, educational, and environmental responsibility [3].

The World Health Organization (WHO) pointed out that the level of air pollution significantly increased worldwide in recent decades, and this has caused approximately seven million people to die annually worldwide due to deteriorating air quality [4]. Previous studies have found that exposure to deteriorating air quality has significant negative impacts on human decision-making performance because a high indoor CO_2 concentration [5], especially particulate matter (PM), can lead to a range of health issues including cardiovascular and respiratory disease and cancers, allergies, and other related ailments [6]. In general, all students, teachers, researchers, and administrative staff in university communities face potential harmful threats and health risks from air quality in the campus environment. Therefore, some researchers have paid significant attention to the environmental monitoring of outdoor and indoor air quality on university campuses recently. Liu et al. [7] adopted both fixed and mobile monitoring sites to analyze spatial and temporal concentration variations of traffic-related $PM_{1.0}$, $PM_{2.5}$, and PM_{10} particulate pollutants caused by vehicle emissions on university campuses. The case study revealed that the spatial decay of $PM_{1.0}$ concentration was slower than that of PM_{10} and $PM_{2.5}$ concentrations, i.e., the air pollution of $PM_{1.0}$ was not easily dispersed. Shah and Mishra [8] presented an environment-monitoring IoT system for prediction, which featured a low power consumption of 25.67 mW and the prediction of $PM_{2.5}$ by machine learning. Wang et al. [9] further investigated the heavy metals Cd, Pb, Mn, Zn, and Cu bound in $PM_{2.5}$ air pollutants in both indoor and outdoor campus environments. The results pointed out that approximately 52% of Cd, 40–43% of Pb, 40–42% of Mn, 34–49% of Zn, and 26–29% of Cu indoors originated from outdoors. That is to say, the heavy metals Cd, Pb, Mn, Zn, and Cu bound in indoor $PM_{2.5}$ air pollutants primarily came from surrounding outdoor emissions. Recently, monitoring workplace environment quality has attracted much attention in smart agriculture, smart manufacturing, and smart medicine, health, and care. In 2020, a design concept of a real-time industrial environment-monitoring system for metal-processing operation was addressed by Almalki [10] for the surveillance of the ambient environment, air quality (AQ), and water quality conditions. MQ-2 CO/SO_2 and NO_X gas sensors, as well as PM $PM_{1.0/2.5/10}$ sensors, were used to monitor the environmental quality of the industrial workplace of a metal factory. Furthermore, Campero-Jurado et al. [11] illustrated an industrial IoT (IIoT) case study with smart helmet personal protective equipment (PPE) by integrating a light sensor, a 6-DoF motion-tracking MPU6050 sensor, and a BME680 multi-sensor module with ESP-32 Wi-Fi module for monitoring environmental conditions of a workplace and fall detection. The observation data were further analyzed using a deep convolutional neural network (ConvNet/CNN) to predict the possible occupational risks. The BME680 device in the proposed Smart Helmet 5.0 platform was used to provide an air quality index (AQI) in compliance with ISO16000-29 [12]—indoor air—Part 29: test methods for VOC detectors. In 2021, Dobrilovic et al. integrated both MQ-2 and MQ-135 gas sensors with ESP8266 modules using WSN technologies with the message-queuing telemetry transport (MQTT) protocol for a model of working environment monitoring in a smart manufacturing system of paper haberdashery [13]. On the other hand, both fixed and mobile environment-monitoring systems for monitoring the microclimate in urban areas of the city of Bolzano, Italy, were presented by Croce and Tondini in the year 2022 [14]. From the viewpoint of cost effectiveness, a Raspberry Pi (RPi) platform was used to aggregate the sensing devices and forward the sensing data through a wireless LoRa network to the environmental data platform (EDP) of Eurac Research. For an environment-monitoring applications on a campus, González et al. [15] adopted a commercially available indoor AQ (IAQ) monitoring BME680 sensor to monitor the ambient temperature, humidity, and IAQ level for volatile organic compound (VOC) detection such as NO_2 and CO, and it facilitated the indication of the IAQ level of the Rovira i Virgili University campus through LoRa network and The Things Network (TTN) platform. Furthermore, Al-Okby et al. adopted both SGP30 and SGP40 gas sensors to measures total VOCs (TVOCs) and indoor air quality (IAQ) index to identify the best and most flexible solution for air quality threshold selection of hazardous/toxic gas detection for IAQ alarm systems [16]. In addition, an SHTC3 was used to measure ambient temperature and humidity. All the acquired data of TVOC, IAQ index and IAQ level, as well as ambient temperature and humidity, were sent to the IoT-cloud system through a WeMos D1 Mini Wi-Fi module and Wi-Fi network. Recently, some commercialized environment-monitoring devices have become available online. For example, Mahajan adopted a commercially available PIM485 with Enviro+ for Raspberry Pi to implement a citizen-centric environment-monitoring IoT system [17]. A BME280 (temperature, pressure, humidity) sensor, LTR-559 (light and proximity) sensor, MICS6814 analog gas sensor, and MEMS microphone were well built in the Enviro+ for Raspberry Pi and a connector for a PM sensor and an SCL/SDA interface to connect additional sensors with the standard I^2C protocol were designed as well. In addition, the SV11 environmental sensor device in Verkada was commercialized and connected to the cloud-based Command platform through a power over Ethernet (PoE) protocol [18]. However, the Enviro+ for the Raspberry Pi platform and Verkada's SV11 environmental sensor module aggregating the VOC sensor, PM sensor, motion detection sensor, temperature/humidity sensor, and noise sensor were not cost-effective in a large-scale implementation. To our best knowledge, heterogeneous integration for diverse sensors for monitoring environmental conditions on a campus, especially in classrooms, can be cost-effectively designed using a commercially available Wi-Fi module and existing Wi-Fi communication networka. This motivates us to develop a DYU Air Box to monitor the learning environment conditions in classrooms at Da-Yeh University, Taiwan using the public ThingSpeak IoT platform. Da-Yeh University was ranked 55 out of 1183 entries by the UI GreenMetric World University Ranking which is a ranking of green campuses and environmental sustainability [19]. The proposed DYU Air Box integrates heterogeneous environmental sensors for learning environments including indoor air quality (IAQ) with AQI value/level, $PM_{1.0}$/$PM_{2.5}$ and CO_2 concentration, as well as illumination, ambient temperature and relative humidity (RH), in order to reach the goals of environmental, social, and corporate governance (ESG) for all stakeholders including the students, faculty, and staff on campus as well as other stakeholders such as the alumni and students' parents. The features are compared with the above publications and tabulated in Table 1. Therefore, the research aims of this work are to simply implement the proposed DYU Air Box on the DYU campus, cooperating with the existing DYU-802.1X campus network and openly provide the environmental information of the DYU campus on the public ThingSpeak IoT platform for all stakeholders. Table 1 reveals that only the proposed wireless environment-monitoring IoT system includes the accessibility of the public ThingSpeak IoT platform through the existing DYU-802.1X Wi-Fi communication network with Wi-Fi Protected Access 2 (WPA2) Enterprise security.

The work is aimed to facilitate the environment-monitoring IoT system of the proposed DYU Air Box and the DYU-802.1X campus Wi-Fi network on the DYU campus to publicly share the environmental information on the ThingSpeak IoT platform for all stakeholders according to their interests. This will positively promote the international ESG impression of DYU. The main contributions of this paper include two aspects: (1) to address the wireless DYU Air Box with multiple environment-monitoring sensors using an ESP32 Wi-Fi device, which is more cost-effective than the two commercially available ones above; (2) to send the acquired data to the public ThingSpeak IoT platform through the DYU-802.1X communication network with WPA2 Enterprise security. The remainder of this paper is organized as follows. First, the system design and the related theory are described in Section 2. Section 3 illustrates the implementation of the wireless DYU Air Box and the visualization of the multi-sensor EMIoT system on the public ThingSpeak IoT platform. In addition, the evaluation results are shown in Section 3. The discussion is given in Section 4. Finally, brief conclusions and future works are given in Section 5.

Table 1. Comparisons of environment-monitoring systems for applications.

Application Scenario	Sensing Layer		Communication Layer	Application Layer	Reference
	Sensors	Processor			
Industry (metal-processing workplace)	MQ-2 CO/SO_2 sensors GP2Y1010AU0F dust sensor DS18B20 temperature sensor Soot particulate NO_X sensor PHE-45P pH sensor AW2T24TEL-4A1 shock sensor	Arduino Due Arduino Nano	ESP8266 Wi-Fi SIM900 GSM	None	Almalki [10]
Industry (Smart Helmet 5.0)	LDR illumination-level sensor ALS-PT19 light sensor BME680 multi-sensor Force-sensitive resistor MPU6050 6-DoF motion sensor	ESP-WROOM-32	Wi-Fi	ThingBoard IoT	Campero-Jurado et al. [11]
Industry (paper haberdashery)	MQ-2 gas sensor MQ-135 gas sensor	WeMos D1 ESPduino NodeMCU	Wi-Fi	Mosquitto MQTT broker	Dobrilovic et al. [13]
Smart cities	HIH6121(fixed)/ PM15PS and SP420 (mobile)	Raspberry Pi (RPi)	LoRa/NBIoT	Environmental DATA PLATFORM (EDP)	Croce and Tondini [14]
Rovira i Virgili University campus	BME680 multi-sensor	LoRa node	TTIG LoRa gateway	The Things Network (TTN)	González et al. [15]
(two chemical labs)	SGP30, SGP40, SHTC3	WeMos D1 Mini	Wi-Fi	IoT-cloud system	Al-Okby et al. [16]
Citizen-centric environment-monitoring IoT system	BME280 temp/humidity/pressure LTR-559 light sensor MICS6814 gas sensor SPH0645LM4H-B sound sensor	Raspberry Pi (+default)	Wi-Fi	ThingSpeak IoT platform	Mahajan [17]
Verkada SV11-HW	VOC sensor PM sensor Motion detection sensor Temp/Humidity sensor Noise sensor	Verkada hardware	Power over Ethernet (PoE)	Cloud-based Command platform	Verkada [18]
DYU Air Box Da-Yeh University	BH1750 light sensor BME680 temp/humidity/AQI sensor SCD30 CO_2 sensor PMS7003T dust sensor	TTGO ESP32	802.1X	ThingSpeak IoT platform	Proposed

2. Materials and Methods

Figure 1 illustrates the scenario for the proposed wireless DYU Air Box for monitoring the environmental conditions of classrooms and visualization on the public ThingSpeak IoT platform through the DYU-802.1X communication network with WPA2 Enterprise security on Da-Yeh University campus. The proposed DYU Air Box is a wireless heterogeneous multi-sensor module which consists of a BH1750 light sensor, a BME680 temperature sensor, an RH and IAQ sensor, an SCD30 CO_2 gas sensor, a PMS7003T dust sensor, and a TTGO ESP32 Wi-Fi device (Lilygo, Hong Kong, China). Firstly, all DYU Air Box modules access the authentication server (AS) through an authenticator for the authentication of an entity through the Enterprise 802.1X communication network. The authenticated DYU Air Box facilitates the forwarding of all environment-monitoring data including AQI value/level, $PM_{1.0}/_{2.5}$ and CO_2 concentration, brightness, ambient temperature, and RH in classrooms to the public ThingSpeak IoT platform for observation. All stakeholders including students, faculty, staff, alumni, and even students' family can easily visualize the real-time environmental information of classrooms at Da-Yeh University. Especially, all students, faculty, and staff on campus can directly access information through the DYU-802.1X communication network. The design details of the hardware and firmware are described as follows.

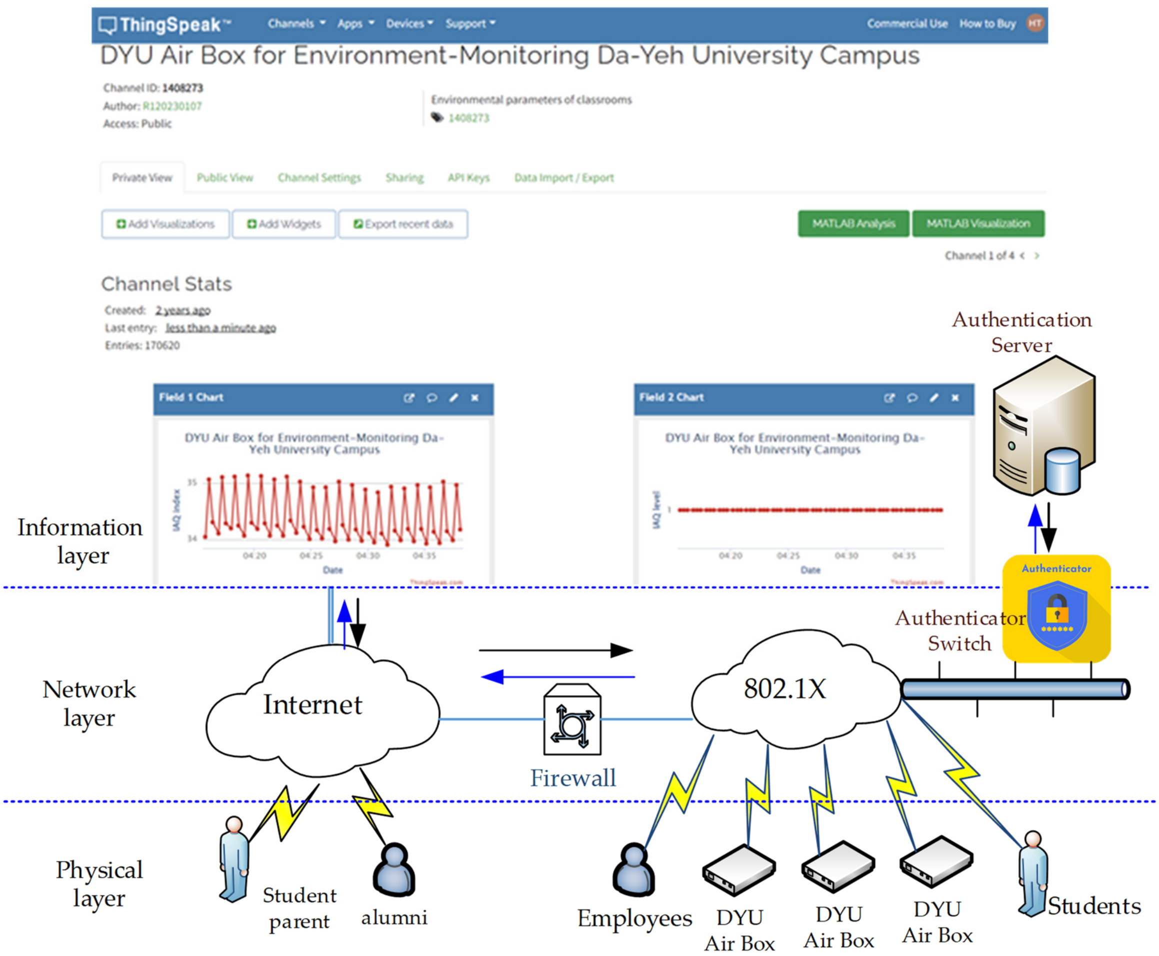


Figure 1. Schematic of wireless multi-sensor EMIoT system on Da-Yeh University campus.

2.1. Hardware Design for DYU Air Box

As shown in Figure 2a, a TTGO ESP32 Wi-Fi module was adopted in the proposed wireless DYU Air Box to aggregate the BME680 temperature sensor (Bosch Sensortec, Kusterdingen, Germany), humidity and IAQ sensor (Tongdy Sensing Technology Corporation, Beijing, China), BH1750 light sensor (Rohm, Kyoto, Japan), SCD30 CO_2 gas sensor (Sensirion, Stäfa, Switzerland), and PMS7003T PM sensor (Panteng Technology, Nanchang, China). The BH1750, BME680, SCD30, and PMS7003T sensing devices were firstly integrated in the TTGO ESP32 shield as shown in Figure 2b which further illustrates a 4-pin 2.54 mm dip header that is assigned to connect the PMS7003T sensor with a UART interface, and three 4-pin 2.54 mm dip headers are arranged for the BH1750, BME680, and SCD30 sensors with the I^2C interface standard. There is a built-in 1.14-inch ISP display with a resolution of 135 $\times$ 240 in the TTGO ESP32 Wi-Fi module, which was connected to the standard SPI interface. The PMS7003T PM sensor with the standard Tx/Rx interface and 5 V_{DC}/GND connections was connected to GPIO 27/26 and 5 V_{DC}/GND of the TTGO ESP32 module. Furthermore, the BH1750, BME680, and SCD30 sensors with the I^2C interface are connected in parallel with the GPIO 22/21 (SCL/SDA) and the 3.3 V_{DC}/GND of the TTGO ESP32 module, respectively. The layout of the DYU Air Box is in the top layer of a PCB board. The shield layout design for the proposed wireless multi-sensor module was carried out using the open-source EasyEDA 6.5.5 software [20], and both top and bottom layers of the resulting PCB layout for the proposed interdisciplinary and heterogeneous sensing module are shown in Figure 2c. As compared to the commercially available PIM485 with Enviro+ for Raspberry Pi, the customized wireless multi-sensor module has the same standard series communication interfaces including all I^2C, UART, and SPI interfaces.

(a)

(b)

(c)

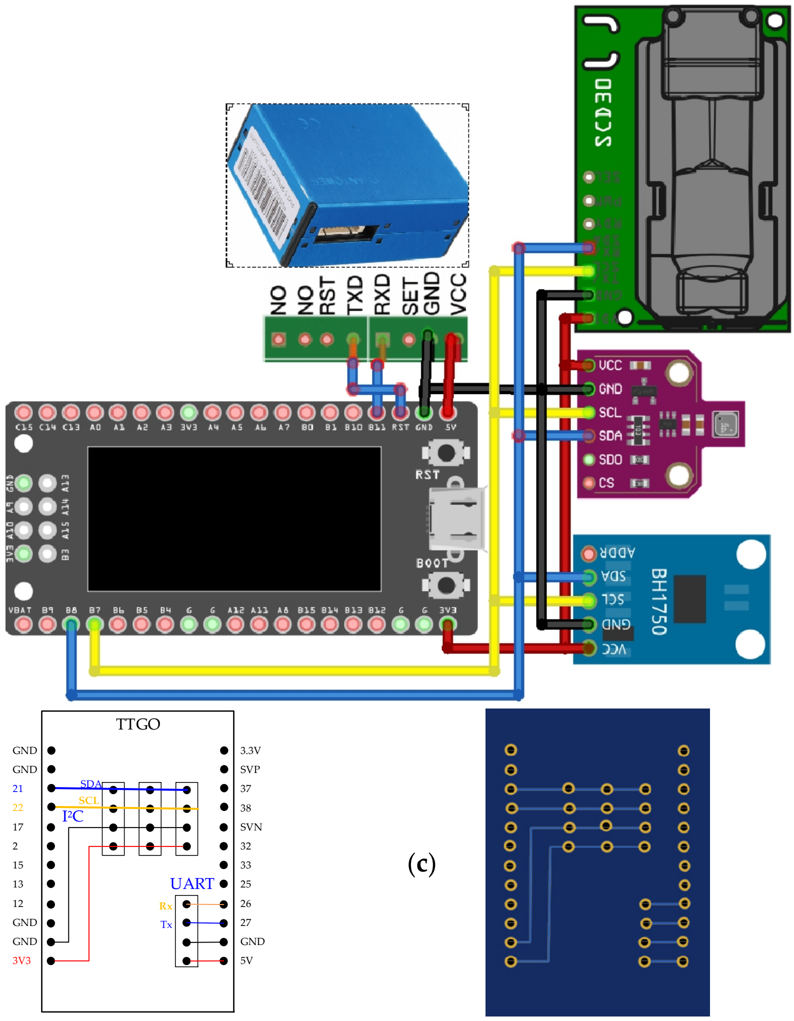


Figure 2. Schematics of wireless DYU Air Box with heterogeneous and multi-sensor module: (**a**) Wiring connection; (**b**) sensor shield; (**c**) PCB layout.

The TTGO ESP32 Wi-Fi module is one of the most compact devices in the EspressIF-ESP32 family with a 240 MHz Xtensa 32-bitLX6 microprocessor-based IoT microcontroller unit (MCU) featuring a low-cost, low-power system on a chip (SoC) microcontroller with 4M-byte flash memory and analog, digital, UART, I^{2}C, and SPI interfaces [21]. Figure 3a shows a digital 4-in-1 BME680 sensor [22] facilitating temperature, humidity, pressure, and gas measurement, in which a single MEMS die with temperature and humidity sensors acquires the ambient temperature and RH parameters. The MEMS die of the BME680 gas sensor is a metal-oxide-based sensor which detects and measures air quality for concentration level of ethanol and breath volatile organic compound (b-VOC) mixtures by absorption and subsequent oxidation/reduction on its sensitive layer; furthermore, the Bosch 2.4.0.0 Software Environmental Cluster (BSEC) algorithm provides an AQI level by taking pressure, temperature, and humidity parameters into consideration. Sensing signal multiplexer, amplification, and I^{2}C/SPI series data communication are implemented by the following application-specific integrated circuit (ASIC). The reading of the temperature sensor is firstly oversampled twice and then goes through a built-in infinite impulse response (IIR) filter which can effectively reduce the bandwidth of the temperature signal and increase the resolution of the digital reading of temperature up to 20 bits. Considering the humidity reading does not fluctuate rapidly, the acquired data of the humidity sensor are directly sampled and converted to a digital reading with 16-bit resolution. It should be noted that the BME680 gas sensor has detection ability for all VOCs/contaminants in the surroundings such as the outgassing of paint, furniture, or garbage. In addition, high VOC levels due to cooking, food consumption, exhaled breath, or salty sweat can be measured well. Based on the Mie scattering theory, the PSM7003T particle concentration sensor [23] adopts laser light to radiate the suspended particles in the air and produce laser scattering light to a certain degree depending on the particle size as shown in Figure 3b. Both equivalent particle diameter and the number of particles with different diameters per unit volume can be calculated by a microprocessor based on Mie theory. Knowing the main absorption wavelength of 4.26 µm for CO_2 gas, the SCD30 CO_2 sensor [24] is an industrial nondispersive infrared (NDIR) CO_2-sensing device which acquires the CO_2 concentration in the range of 400–10,000 parts per million (ppm). As shown in Figure 3c, the SCD30 CO_2 sensor uses an infrared (IR) lamp to direct IR light waves through a tube filled with a sample of air, the CO_2 gas molecules absorb the specific band of IR light while letting other wavelengths of IR light pass through, the remaining light is absorbed by an optical filter except the wavelength absorbed by CO_2 molecules in the sample tube, and a fingerprint is detected by the following CMOS device to identify the CO_2 molecules. A built-in SHT31 temperature and humidity sensor is mainly used to compensate the CO_2 reading; furthermore, the ambient temperature and humidity readings can be used for environment information. It should be noted that CO_2 concentration is one of the most important indicators for IAQ standards. A BH1750 ambient light sensor was used to detect the brightness of light in the range of 1–65,535 lux with high accuracy of 1 lux in the environment [25]. As shown in Figure 3d, the BH1750 light sensor mainly adopts a photodiode (PD) which is a light-sensitive semiconductor device with a p-type–intrinsic–n-type (P-I-N) junction structure in which an intrinsic semiconductor is sandwiched between p-type and n-type ones. The PD devices work in a reversed mode and absorb visible light to produce a current through the effect of photon impact. Then, the photo-generated current is converted to voltage through a two-stage operation amplifier (OP Amp) by integrating an integral OP Amp and an inverter OP Amp. Finally, both an analog-to-digital converter (ADC) and digital circuit with I^2C interface convert the light intensity into digital data according to the I^2C serial communication protocol. The main specifications of the sensors are tabulated in Table 2. I^2C is synchronous and a multi-master/multi-slave serial communication bus. On the other hand, UART has asynchronous serial communication by sending data frames from the least significant to the most significant with both start and stop bits at precise times. Figure 2a illustrates that only the PMS7003T dust sensor is arranged with the GPIO 26 (Rx) and DGPIO 27 (Tx) pins with the UART interface of the programmed sensor shield for the TTGO ESP32 Wi-Fi module. The others are assigned to GPIO 21 (SCL) and GPIOv22 (SDA) pins in any one of the I^2C interfaces which can be extended with the same I^2C-interface devices. One SPI interface was well planned for the built-in 1.14-inch ISP display with a resolution of 135 × 240. It is well known that the UART protocol is a master–slave configuration and only one device can be connected to the TTGO ESP32 Wi-Fi module. Furthermore, the I^2C protocol is a multi-master/multi-slave serial communication protocol extending up to 128 devices with the I^2C interface. Moreover, the SPI protocol is similar to the I^2C one with multi-master/multi-slave serial communication but only one device can be enabled to transmit data at a single response time.

Table 2. Main specifications and warning ranges of sensors.

Sensor Types	Sensing Parameter	Measuring Range	Accuracy	Temperature/Humidity	Warning Range
BH1750	Brightness	1–65,535 lux	1 lux	−40–85 °C/0–99%	<10 lux or >10,000 lux
BME680	Temperature	−40–85 °C	±0.5 °C	−40–85 °C/0–99%	<0 °C or >40 °C
	Humidity	0–100%	±3%		<20 or >99
	IAQ index	0–500	1		≥151
SCD30	CO_2 concentration	400–10,000 ppm	±50 ppm	0–50 °C/0–99%	≤450 ppm
PMS7003T	PM1.0	0–500 µg/m^3	1 µg/m^3	−10–60 °C/0–99%	≥35 µg/m^3
	PM2.5	0–500 µg/m^3	1 µg/m^3		≥10 µg/m^3

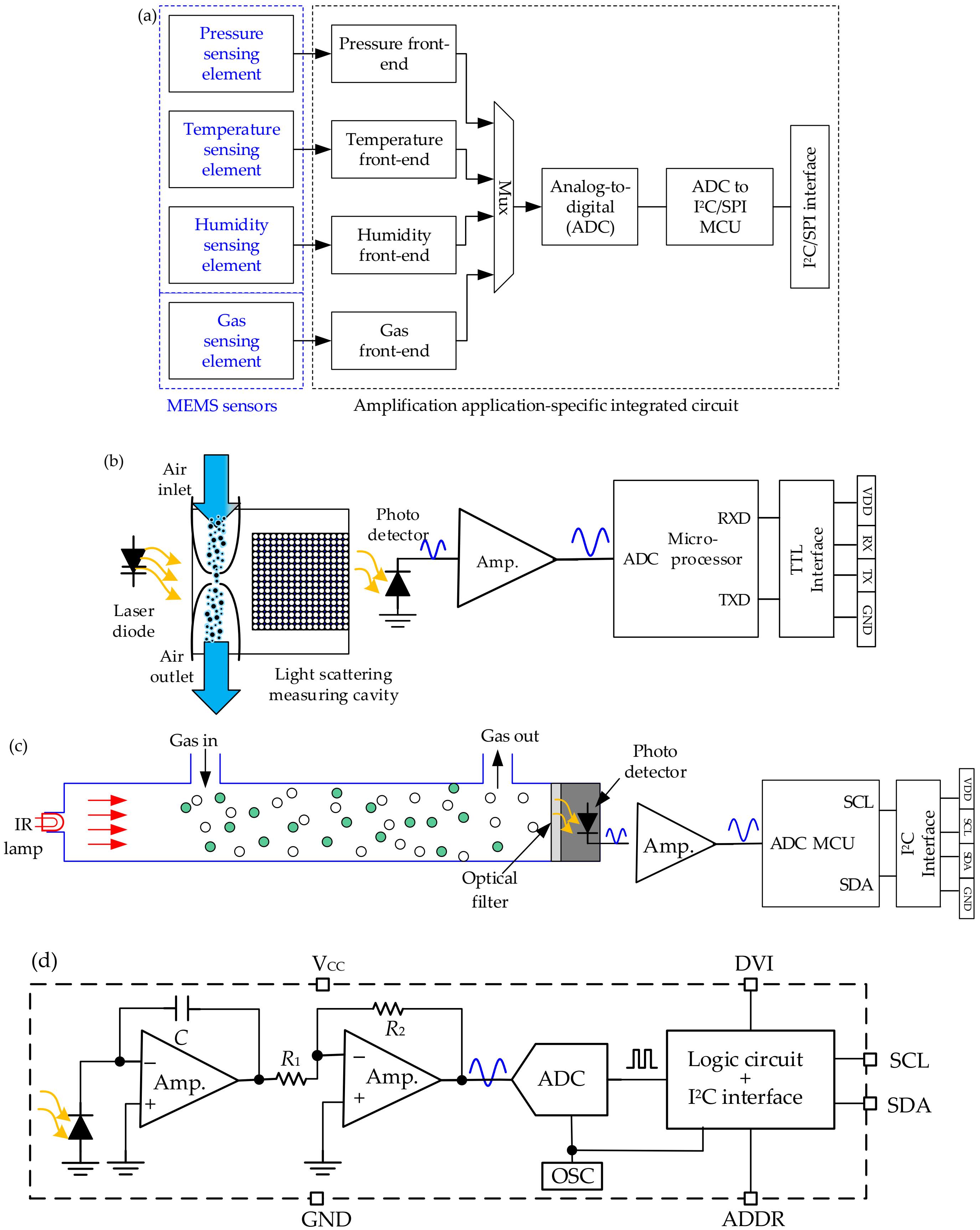


Figure 3. Schematics of heterogeneous sensors: (**a**) BME680 air quality sensor; (**b**) PMS7003T dust sensor; (**c**) SCD30 CO_2 gas sensor; (**d**) BH1750 light sensor.

The TTGO ESP32 module was adopted as an MCU, Wi-Fi/Bluetooth communication platform and a local display device in charge of receiving and displaying the sensing data from BH1750, BME680 air quality, and SCD30 CO_2 gas sensors as well as the PMS7003T dust sensor and forwarding the observation data to the ThingSpeak IoT API through a neighboring 802.1X campus network. The pin assignment of the Wi-Fi module for the sensors is well defined in the datasheet. The programmable ESP32-based LX6 microcontroller was designed to feature the functions of both automatic warning and line notification, which could be implemented by the code programming as explained later. The main specifications of the BH1875 light sensor, BME680 and SCD30 CO_2 gas sensors, and PMS7003T dust sensors for the proposed wireless environment-monitoring system are listed in Table 2. Due to the limit of operation conditions for the SCD30 CO_2 sensor, the operating temperature for the proposed multi-sensor sensing module is suggested in the range of 0–50 °C. The suggested warning ranges of corresponding sensors are also predefined and tabulated in Table 2. The warning ranges of the light, temperature, humidity, dust, and CO_2 concentration levels as well as AQI parameter are listed in Table 2. Table 3 tabulates the AQI classification available in the datasheet of BME680 [22], which is in compliance with the AQI Code of Taiwan [26]. For the DYU-802.1X configuration, the authenticated SSID and password are checked in advance and are coded in the code programming later.

Table 3. AQI criteria.

AQI Level	AQI Value	Air Quality	Impact (Long-Term Exposure)
1	0–50	Excellent	Pure air; best for well-being
2	51–100	Good	No irritation or impact on well-being
3	101–150	Lightly polluted	Reduction of well-being possible
4	151–200	Moderately polluted	More significant irritation possible
5	201–350	Severely polluted	More severe health issues possible if harmful VOCs present
6	>350	Extremely polluted	Headache, additional neurotoxic effects possible

2.2. Firmware Design for Wireless Multi-Sensor EMIoT System with DYU Air Box

The design of the proposed DYU Air Box for monitoring environmental conditions of classrooms on Da-Yeh University campus can be programmable through Arduino platforms under the open-source Arduino integrated development environment (IDE) which supports the code programming languages C and C++ with specified rules of code structure. After the installation of the CP210x USB-to-UART Bridge driver and third-party Wi-Fi platform drive packages in the Arduino IDE environment, the Arduino 1.8.16 software for the proposed wireless DYU Air Box for monitoring the AQI index/level, $PM_{1.0}/PM_{2.5}$ and CO_2 concentration, brightness, ambient temperature, and humidity in classrooms was developed in the same coding configuration and development environment. The libraries of the BME680, PMS7003T, SCD30, and BH1750 sensors as well as WPA2 Enterprise connection available online were included in the beginning of code programming as shown in the flowchart of Figure 4. The observation data were simultaneously displayed in the built-in ISP display of the TTGO ESP32 module and sent to the open-source ThingSpeak IoT platform through the DYU-802.1X network with the standardized ThingHTTP protocol. It is well known that HTTP was designed to make documents available over a client–server protocol across the internet, which both run over the transmission control protocol (TCP). On the other hand, the other MQTT protocol was initially created for IoT applications. The main differences between HTTP and MQTT protocols are tabulated in Table 4.

Furthermore, the flowchart of data acquisition, transmission, and demonstration for the proposed wireless DYU Air Box and the DYU EMIoT system on the public ThingSpeak IoT platform for monitoring environmental conditions of classrooms is depicted in Figure 4. It should be noted that the sending of the observation data to the public ThingSpeak IoT platform is directly programmed and they are downloaded into the TTGO ESP32 Wi-Fi module. The DYU EMIoT system in the public ThingSpeak IoT platform for environmental monitoring of classroom conditions can be configured based on the well-designed format for channel configuration.

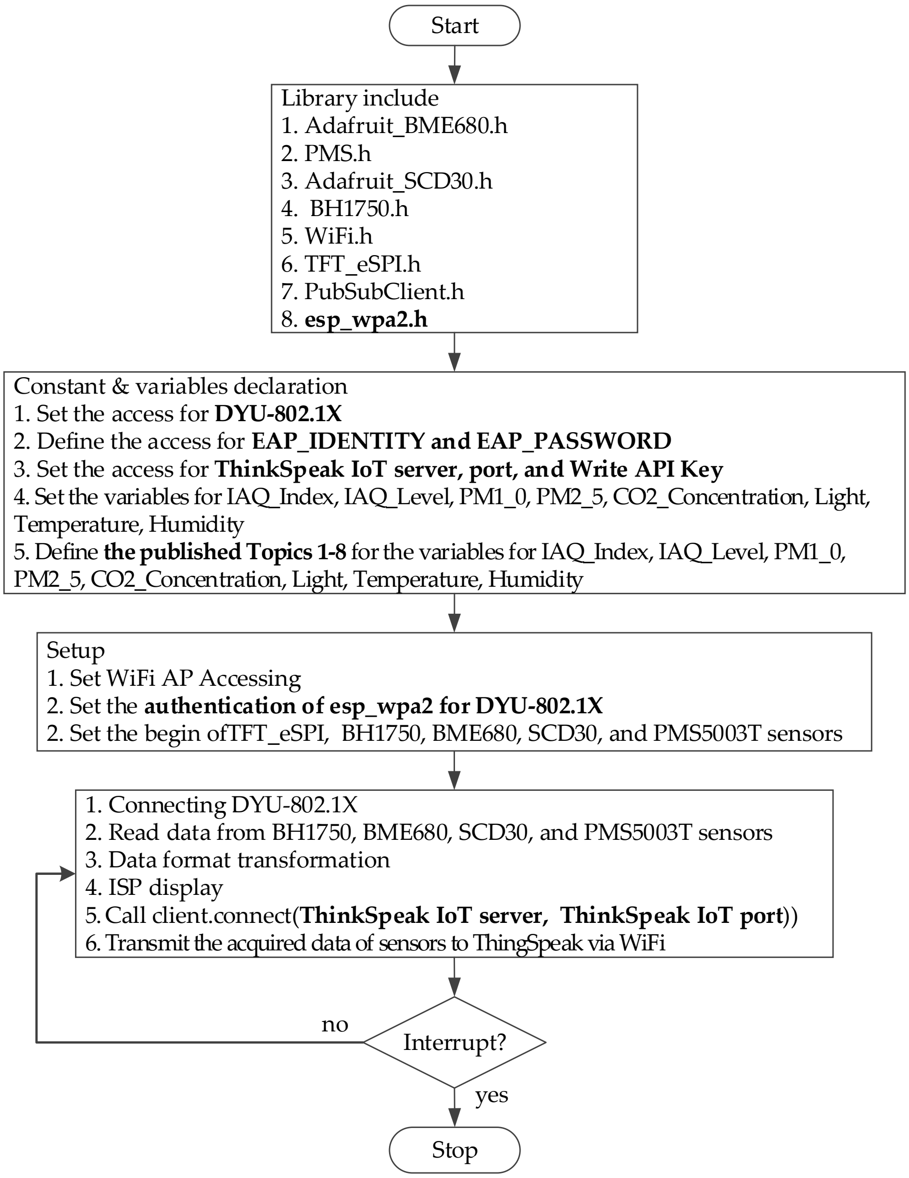


Figure 4. The flowchart of the proposed wireless DYU Air Box.

Table 4. Comparisons between MQTT and HTTP technologies.

Items	HTTP	MQTT
Architecture	Client–server	Publish/Subscribe
Command targets	URIs	Topics
Underlying protocol	TCP/IP	TCP/IP
Secure connections	TLS + username/password	TLS + username/password
Client observability	Unknown connection status	Known connection status
Messaging mode	Synchronous	Asynchronous, event-based
Message queuing	Application needs to implement	The broker queues messages for disconnected subscribers
Message overhead	8 bytes minimum. Header data are text-compressed	2 bytes minimum. Header data can be binary
Message size	Over 256 MB is normal	256 MB maximum
Content type	Text (base64 binary encoding)	Any (binary)
Message distribution	One to one	One to many

2.3. Close-Agreement between DYU Air Box and Commercialized Measurement Instruments

In order to evaluate the in situ sensing accuracy of the proposed DYU Air Box, the agreement between the acquired data and measurement ones of commercialized instruments including a TES-5322A IAQ meter (TES Electrical Electronic Corp., Taipei, Taiwan), a TES-5110 particle counter, a TES-1370H CO_2 m, a TES-1337B light intensity meter, and a TES-1364 temperature and humidity meter [27] was analyzed. Taking the measurement results of the above measurement instruments as references, the relative difference between the proposed DYU Air Box and the corresponding instruments is defined as

$$e_j^n = x_j^n - \hat{x}_j^n \tag{1}$$

where x_j^n and $\hat{x}_j^n$ are the jth measurement values of the proposed DYU Air Box and the corresponding measurement instruments, $j = I_{AQI}, L_{AQI}, PM_{1.0}, PM_{2.5}, CO_2, \lambda, T$, RH. Furthermore, the performance indexes of mean absolute error (MAE), mean absolute percentage error (MAPE) [28], and root mean square error (RMSE) for close-agreement analysis are defined as

$$\text{MAE} = \frac{1}{N}\sum_{n=1}^{N}\left|x_j^n - \hat{x}_j^n\right| \tag{2}$$

$$\text{MAPE} = \frac{100\%}{N}\sum_{n=1}^{N}\frac{\left|x_j^n - \hat{x}_j^n\right|}{\hat{x}_j^n} \tag{3}$$

and

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(x_j^n - \hat{x}_j^n\right)^2} \tag{4}$$

where N is the observation number. The results of statistical analysis of the agreement between the proposed DYU Air Box and the above commercially available measurement instruments will be presented later.

3. Results

The proposed DYU Air Box is aimed to provide environment information including the AQI value and level, $PM_{1.0}/PM_{2.5}$ concentrations, CO_2 concentration, brightness, ambient temperature, and RH on the DYU campus for stakeholders including the students, faculty, and staff on campus as well as other stakeholders such as alumni and students' parents. The H708 classroom at DYU was adopted as a case-study field for environmental monitoring using the DYU Air Box. Therefore, the above eight parameters were assessed in this work. In general, the classroom is semi-open, i.e., the environmental conditions are dynamically time-varying and can be closely affected by the ambient environment and artificially controlled by manpower like environment-controlled facilities such as illumination as well as heating, ventilation, and air conditioning (HVAC). The assessment for the above eight parameters of environment conditions in the H708 classroom was as follows.

3.1. Implementation of Proposed Wireless DYU Air Box

First of all, the BH1750, BME680, SCD30, and PMS7003T sensors as well as the TTGO ESP32 Wi-Fi device were aggregated in the well-designed PCB board. The implemented hardware of the proposed wireless, interdisciplinary, and heterogeneous multi-sensor monitoring module is shown in Figure 5. Figure 5a illustrates that the BME680 AOI/temperature/humidity sensor, PMS7003T $PM_{1.0}/PM_{2.5}$ sensor, SCD30 CO_2 sensor, and BH1750 light sensor were integrated into an ESP32 Wi-Fi module with four standard 4-pin socket terminals of 2.54 mm. Such a design means the devices can be easily removed for testing and maintenance. Figure 5b presents that the proposed multi-sensor monitoring module can be arranged on a decorated platform such as the DYU Air Box. The acquired data of the AQI value and level, $PM_{1.0}$ and $PM_{2.5}$ concentrations, CO_2 concentration, brightness, ambient temperature, and humidity could be directly read by the TTGO ESP32 Wi-Fi module through the same I^2C interface. In addition, the data acquisition of $PM_{1.0/2.5}$ from the PMS7003T dust sensor was read by the same Wi-Fi module through the UART interface. The proposed wireless DYU Air Box has been evaluated in the H708 teaching classroom at Da-Yeh University over two months starting on 1 October 2023. The accuracy of the AQI value and level, the concentrations of $PM_{1.0}$, $PM_{2.5}$, and CO_2, as well as brightness, temperature, and humidity was validated using commercially available instruments: a TES-1337B light intensity meter, a TES-1364 temperature and humidity meter, a TES-1370H CO_2 meter, a TES-5110 particle counter, and a TES-5322A IAQ meter.

(a) (b)

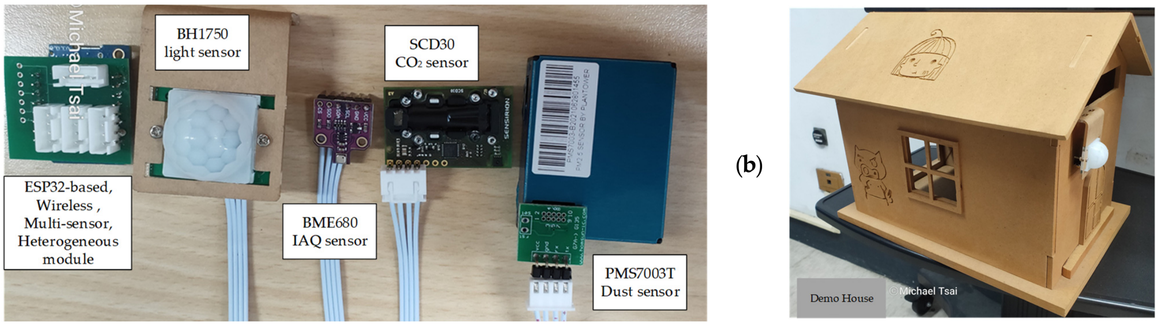


Figure 5. Photographs of the proposed wireless heterogeneous multi-sensor module: (**a**) TTGO ESP32 Wi-Fi module, BH1750 light sensor, BME680 AQI sensor, SCD30 CO_2 sensor, and PMS7003T dust sensor; (**b**) demo DYU Air Box for environmental monitoring of classroom.

3.2. In Situ Monitoring Results

In order to double-check the accuracy, confidence, and reliability of the proposed wireless DYU Air Box for monitoring environmental conditions of the classroom, the multi-sensor module including the BME680, PMS7003T, SCD30, and BH1750 sensors was evaluated using the above measurement instruments in the H708 teaching classroom from 1–31 October 2023. The observation data of in situ monitoring were forwarded to the public ThingSpeak IoT platform through the 802.1X Wi-Fi network. Therefore, the observation data of the IAQ value and IAQ level, $PM_{1.0}/PM_{2.5}/CO_2$ concentrations, brightness, ambient temperature, and humidity in the H708 classroom could be easily accessed in the environment of the ThingSpeak IoT platform. All on-site observations of sensing parameters were carried out at 1 min intervals in a 30-consecutive-day in situ experiment and then forwarded to the ThingSpeak IoT platform (channel ID: 1408273, available online: https://thingspeak.com/channels/1408273, accessed on 15 December 2023) [29] through the built-in 802.1X Wi-Fi network on campus. The proposed multi-sensor module was set up to monitor the environmental conditions in the classroom including IAQ index/level, $PM_{1.0/2.5}$ concentration, CO_2 concentration, brightness, temperature, and humidity. A screenshot of the ThingSpeak public channel for the environment-monitoring IoT system of the proposed DYU Air Box is shown in Figure 6. The observation data can be downloaded and further analyzed using MATLAB 2019b software or other big data analytics software packages. Taking the study case on 16 October 2023 as an example, the IAQ index and IAQ level, $PM_{1.0/2.5}$ and CO_2 concentration, brightness, temperature, and humidity were well exported and reconstructed using MATLAB 2019b software in a 24 h time frame in the H708 classroom in which the light intensity was almost synchronized with the sunrise at about 06:00 a.m., increased to the maximal brightness until 13:00 p.m. with east–south exposure, and became dark near 17:00 p.m. after work ended. The light was kept turned off until dawn next day and only at 17:35 did the security guard on campus turn on the light for a check. It should be noted that the brightness in the classroom is the combination of man-made illumination and solar irradiance; therefore, the brightness over 1000 lux between 10:10 and 14:00 partly came from the contribution of solar irradiation. The inlet of sunlight could increase the indoor temperature. As shown in Figure 7g, the indoor temperature started to soar after sunrise. The temperature was preset at 28 °C and controlled near 28 °C. Figure 7g further reveals the indoor temperature increased a little over the preset one and reached up to 29.4 °C, caused by the incoming solar irradiation. In addition, there is a 30 min time-delay response between brightness and ambient temperature which was caused by the thermal mass in the indoor thermodynamics. The humidity parameters shown in Figure 7h approximately reveal a close inverse proportion in contrast to the ambient temperature. The humidity reached the lowest level at 13:00 p.m. as the ambient temperature simultaneously rose up to 29.4 °C. The information of brightness, temperature, and humidity as shown in Figure 7f–h distinctly illustrates the comfort level in the H708 classroom under control and surveillance.

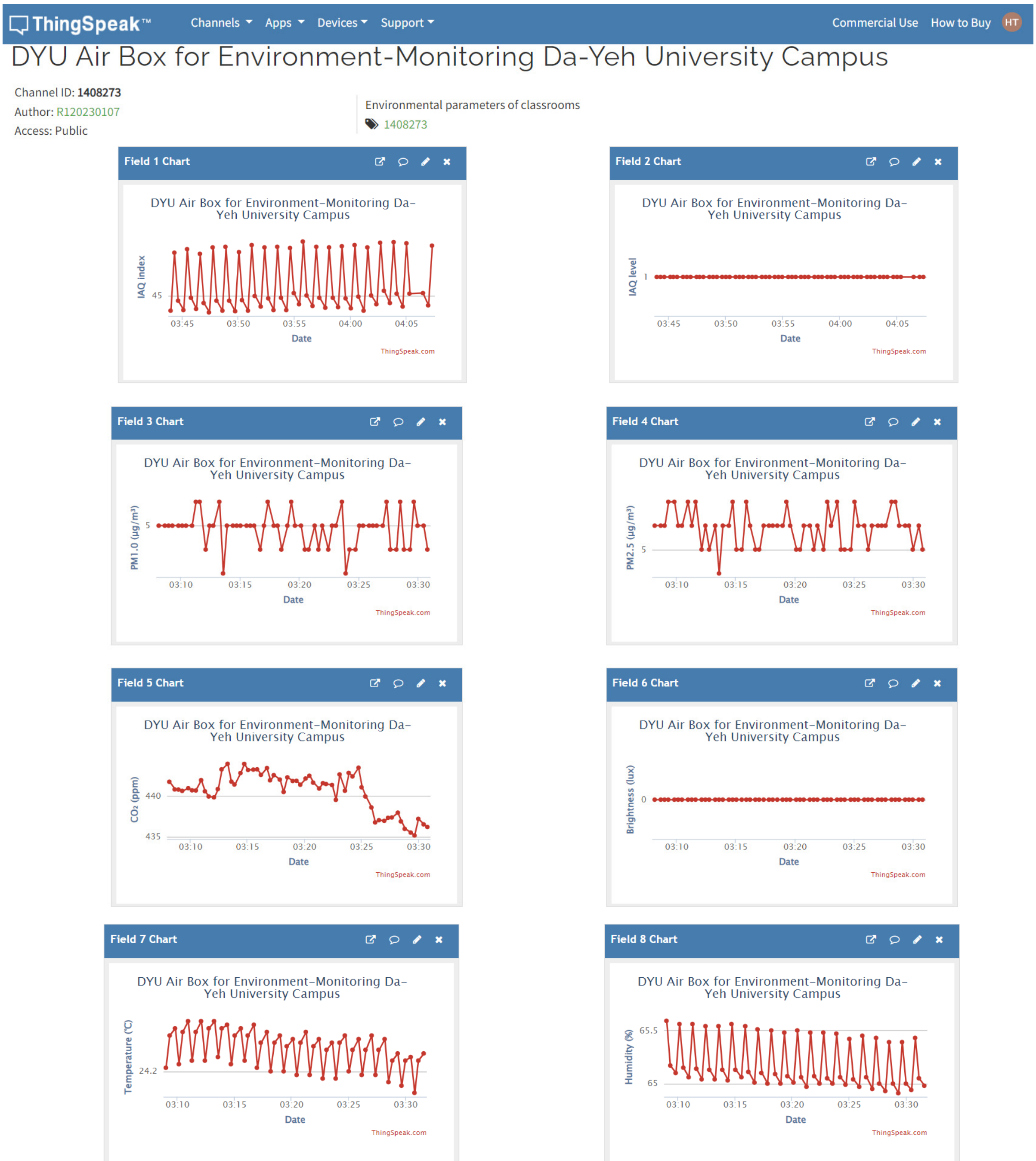


Figure 6. Screenshot of the ThingSpeak public channel for the proposed DYU Air Box.

Figure 7. *Cont.*

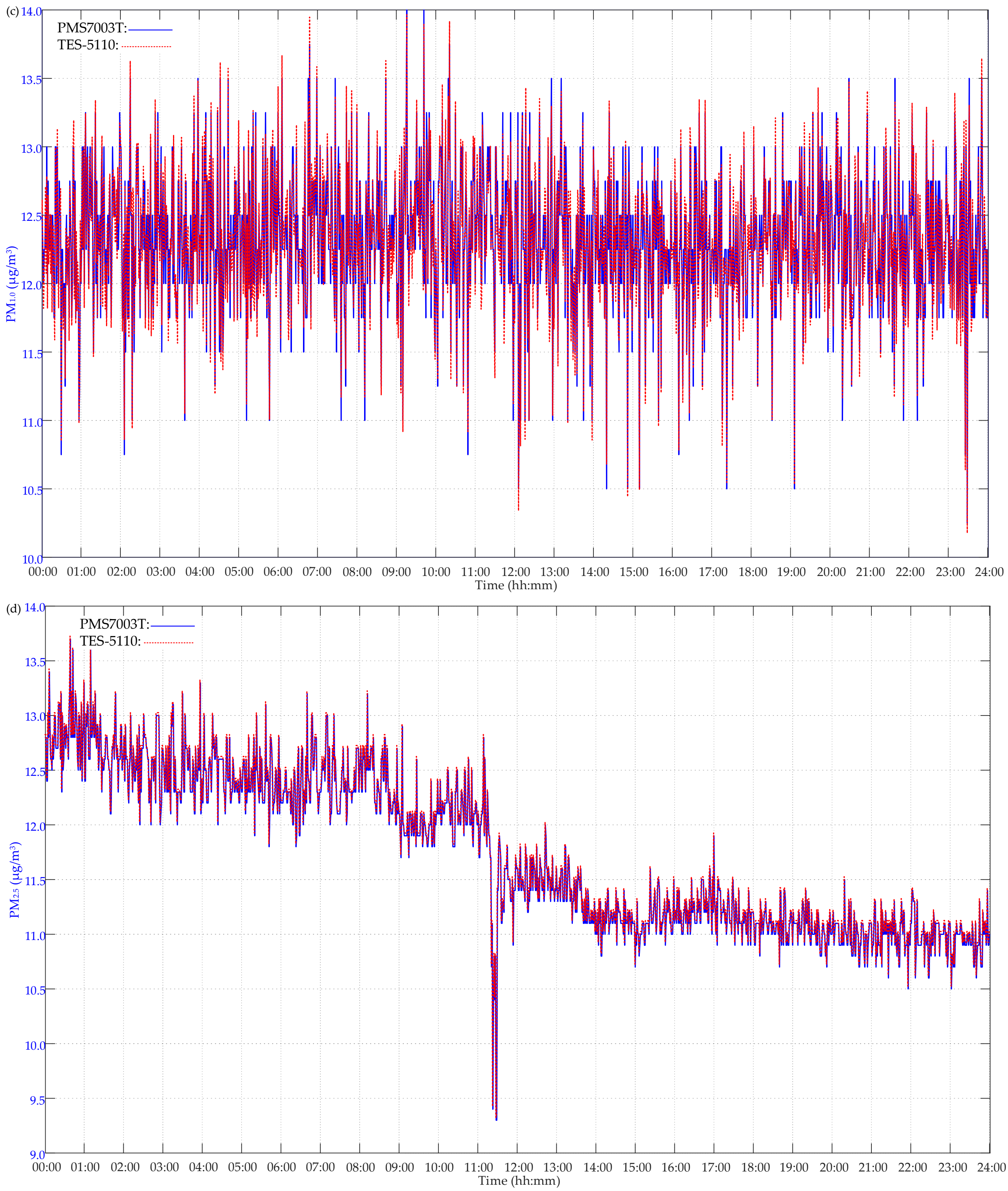
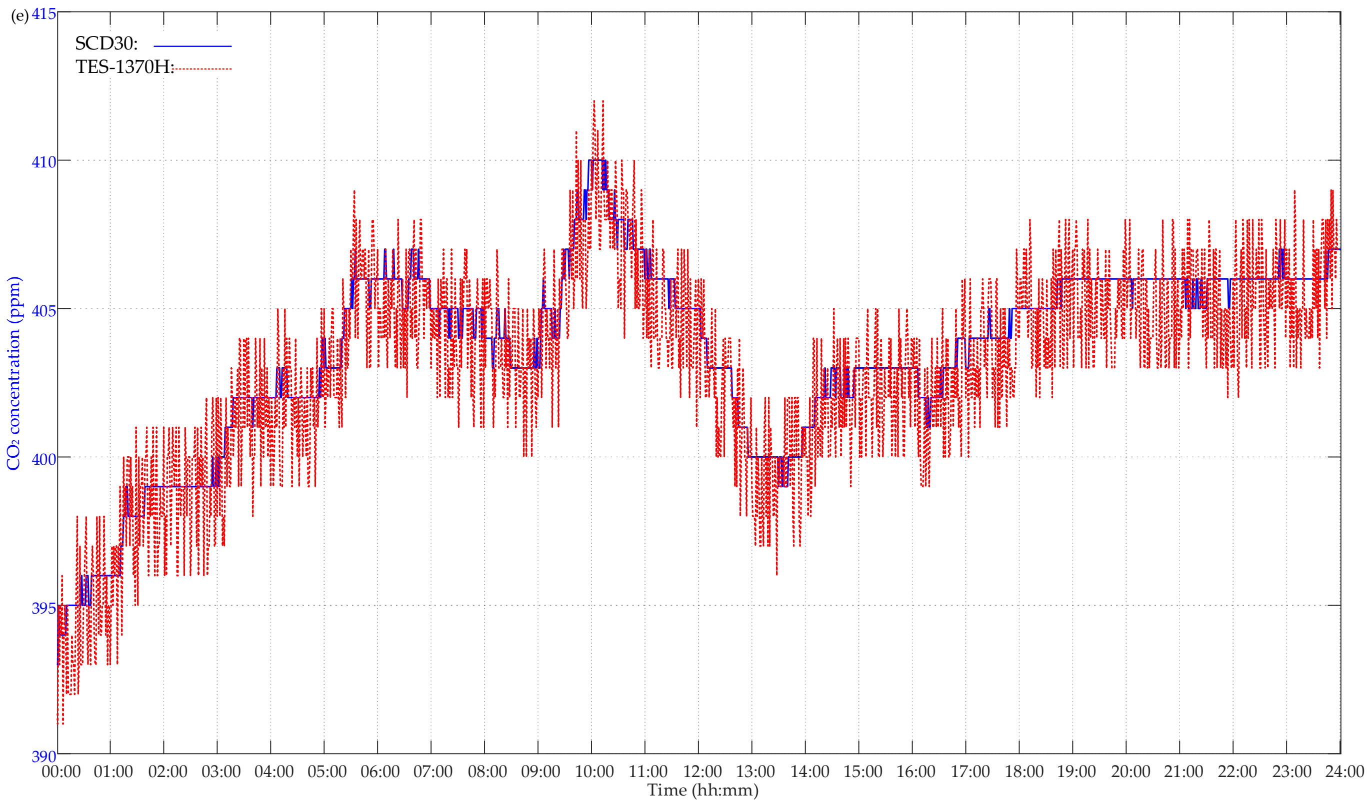


Figure 7. *Cont.*



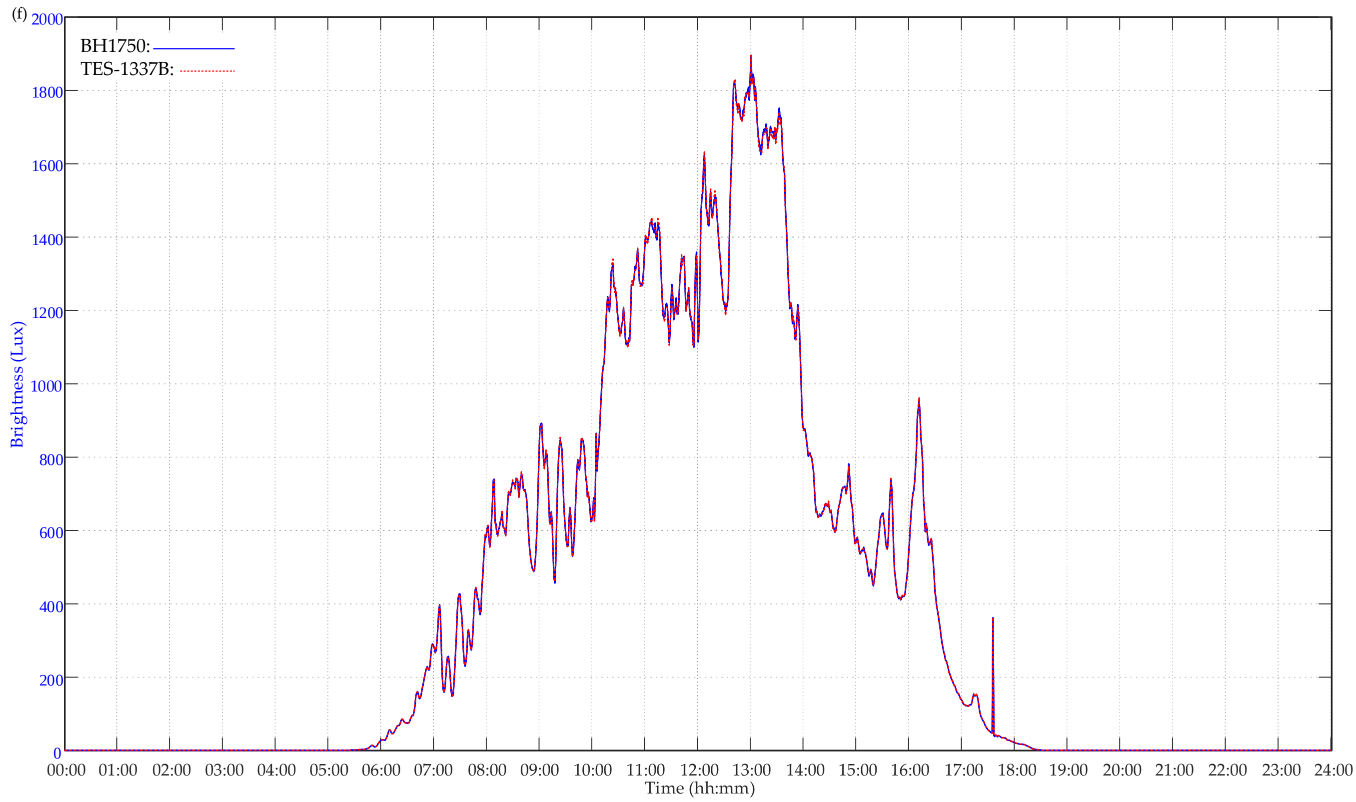


Figure 7. *Cont.*

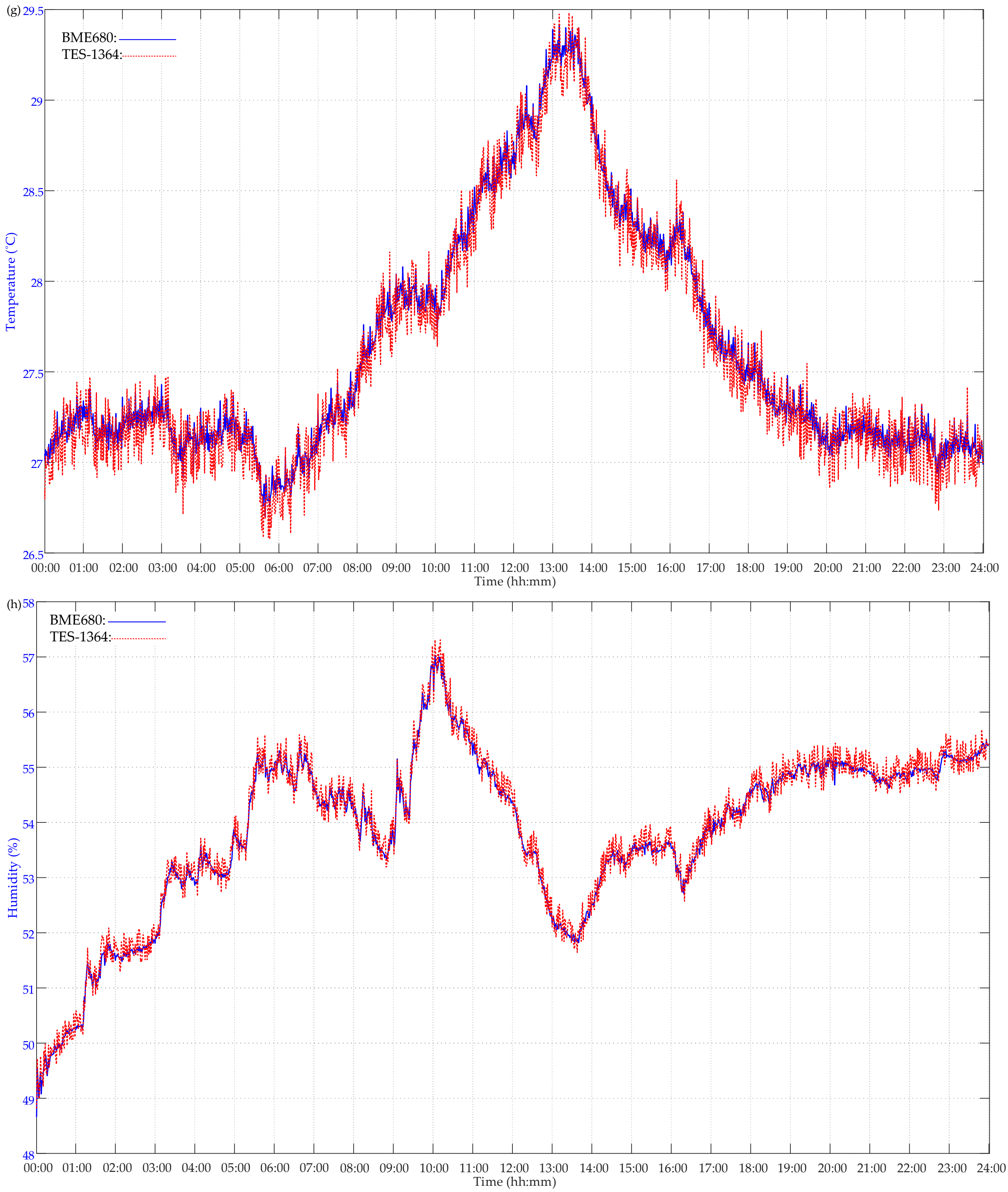


Figure 7. The 24 h in situ measurement results of DYU Air Box for environmental monitoring of H708 classroom at Da-Yeh University: (**a**) IAQ index; (**b**) IAQ level; (**c**) $PM_{1.0}$ concentration; (**d**) $PM_{2.5}$ concentration; (**e**) CO_2 concentration; (**f**) brightness; (**g**) temperature; (**h**) humidity.

3.3. Close-Agreement Analysis between DYU Air Box and Commercial Instruments

In order to double-check the agreement, confidence, and reliability of the proposed DYU Air Box, the acquired IAQ index, $PM_{1.0}$ and $PM_{2.5}$ concentrations, CO_2 concentration, brightness, temperature, and humidity were simultaneously measured using the corresponding measurement instruments: TES-5322A IAQ meter, TES-5110 particle counter, TES-1370H CO_2 meter, TES-1337B light intensity meter, and TES-1364 temperature and humidity meter, which are commercially available. The readings are depicted in Figure 7a,c–h. In order to easily analyze the agreement between the DYU Air Box and commercial measurement instruments, the differences of IAQ index, $PM_{1.0}$ and $PM_{2.5}$ concentrations, CO_2 concentration, brightness, temperature, and humidity are depicted in Figure 8.

Taking the measurement results of the above measurement instruments as references, the relative difference between the proposed DYU Air Box and the corresponding instruments is defined in Equation (1). The corresponding performance indexes of the MAE, MAPE [29], and RMSE for close-agreement analysis are also defined in Equations (2)–(4). As shown in Figure 8a, the reading difference of IAQ level between the DYU BME680 AQI sensor and TES-5322A IAQ meter ranges from −0.1396 to 0.1002; therefore, the related MAE and RMSE values are 0.06 and 0.07, respectively. Moreover, the corresponding MAPE value is 0.31%, which means the agreement of measurement results between the BME680 sensor in the proposed DYU Air Box and TES-5322A IAQ meter can reach up to 99.29%. Because the readings of IAQ in the H708 classroom at Da-Yeh University are far below the threshold value of 50, the IAQ levels of the BME680 sensor in the DYU Air Box and TES-5322A IAQ meter are the same which makes the differences between them zeros as shown in Figure 8b. Therefore, the values of MAE, MAPE, and RMSE for IAQ level are 0. The MAPE for IAQ level is 0 as well. Figure 8c,d illustrate that the difference ranges of $PM_{1.0}$ and $PM_{2.5}$ concentrations between the PMS7003T sensor in the DYU Air Box and TES-5110 particle counter are −0.1157–0.1183 $\mu g/m^3$ and −0.1182–0.11201 $\mu g/m^3$, respectively. Their corresponding MAE/RMSE values are, respectively, 0.06/0.07 $\mu g/m^3$ and 0.06/0.07 $\mu g/m^3$; therefore, the MAPE values of $PM_{1.0}$ and $PM_{2.5}$ concentrations are 0.37% and 0.50%, respectively. This means the PMS7003T sensor in the DYU Air Box can provide measurements of $PM_{1.0}$ and $PM_{2.5}$ concentrations that are up to 99.6% and 99.5% similar to those of the commercialized TES-5110 particle counter. As shown in Figure 8e, the measurement difference of CO_2 concentrations between the SCD30 CO_2 sensor in the DYU Air Box and TES-1370H CO_2 meter is −3–4 ppm with the related values of MAE and RMSE being 1.48 ppm and 1.72 ppm, respectively. The resulting MAPE is 0.35% which reveals the corresponding measurement similarity of up to 99.65% between the SCD30 CO_2 sensor in the DYU Air Box and TES-1370H CO_2 meter. The above close agreement of CO_2 concentrations and IAQ criteria including AQI value/level and $PM_{1.0}/PM_{2.5}$ concentrations significantly reveals the measurement confidence of the SCD30, BME680, and PMS7003T sensors in the proposed DYU Air Box. On the other hand, the illumination difference is depicted in Figure 8f which illustrates the difference range is between −15.77 lux and 17.32 lux. Therefore, the corresponding MAE, RMSE, and MAPE are 1.83 lux, 3.70 lux, and 0.25%, respectively. The MAPE of 0.25% for brightness means the BH1750 light sensor in the proposed DYU Air Box can offer measurements that are 99.75% similar to those of the commercialized TES-1337B light intensity meter. Furthermore, Figure 8g,h reveal the temperature and humidity measurement differences between the DYU Air Box and TES-1364 temperature and humidity meter. Figure 8g illustrates the temperature differences between the DYU Air Box and measurement instrument, with a difference range of −0.1758–0.2280 °C and the corresponding MAE and RMSE of 0.10 °C and 0.12 °C, respectively. The temperatures between the BME680 sensor in the proposed DYU Air Box and TES-1364 instrument are 99.34% similar with a MAPE value of 0.66%. Moreover, the humidity difference between the DYU Air Box and TES-1364 humidity meter is shown in Figure 8h, with a difference range of −0.3894–0.2767% over a 24 h measurement period and MAE, RMSE, and MAPE values of humidity analysis of 0.16%, 0.19%, and 0.31%, respectively. The sensing ability of the BME680 sensor of the proposed DYU Air Box has a close agreement of 99.60% with the commercially available TES-1364 humidity meter. The comfort level in the classroom such as illumination, ambient temperature, and humidity can be well monitored by the proposed DYU Air Box like the commercialized instruments.

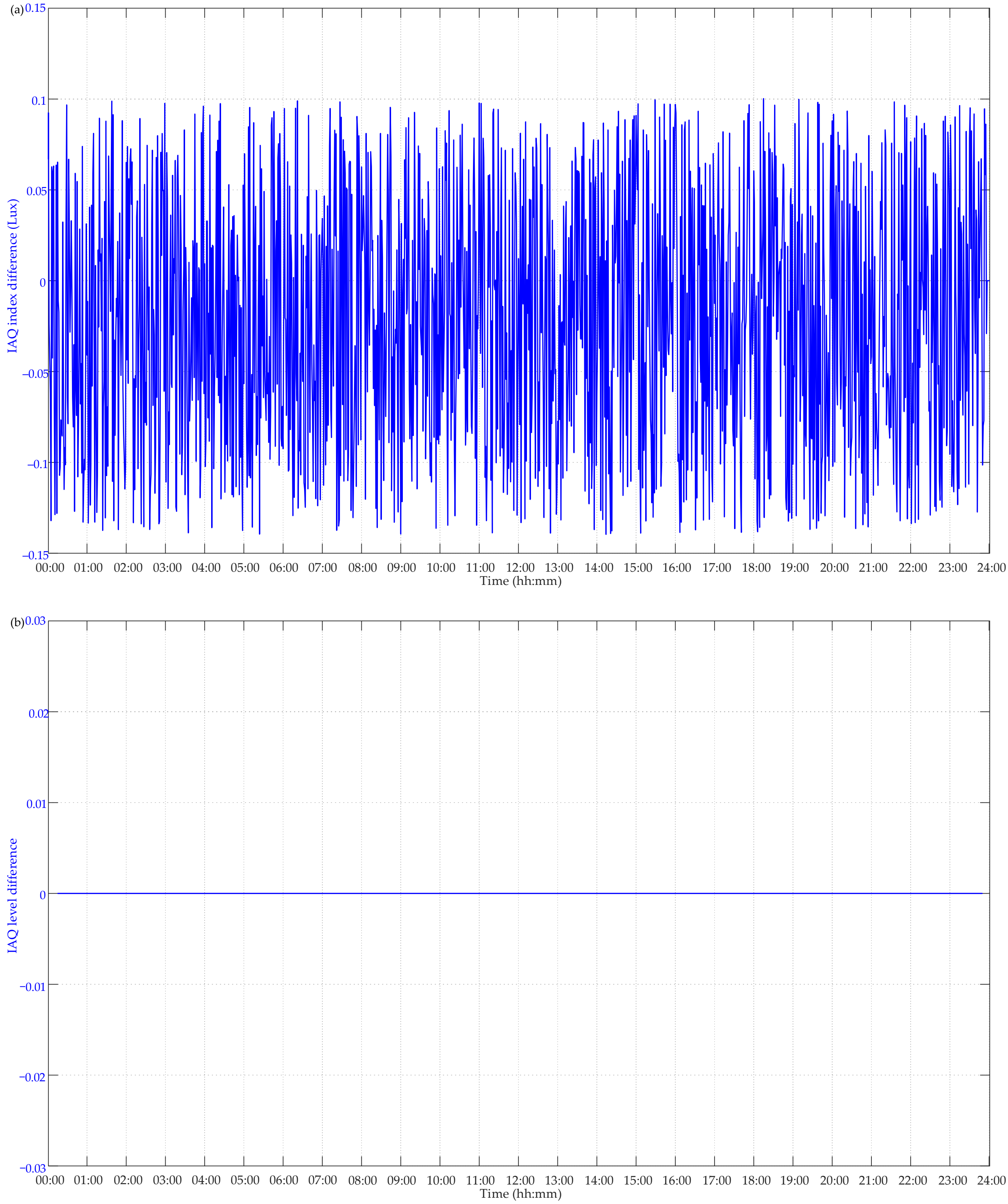
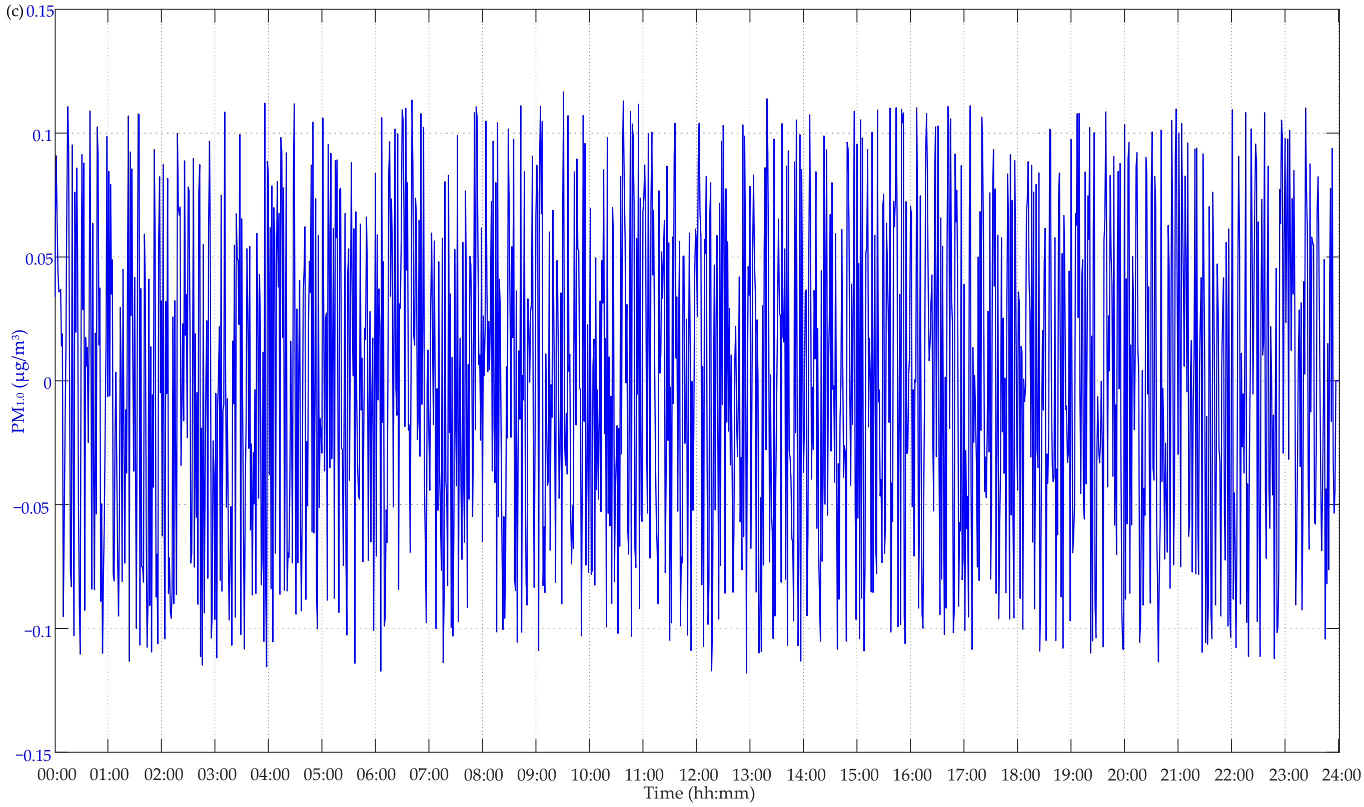
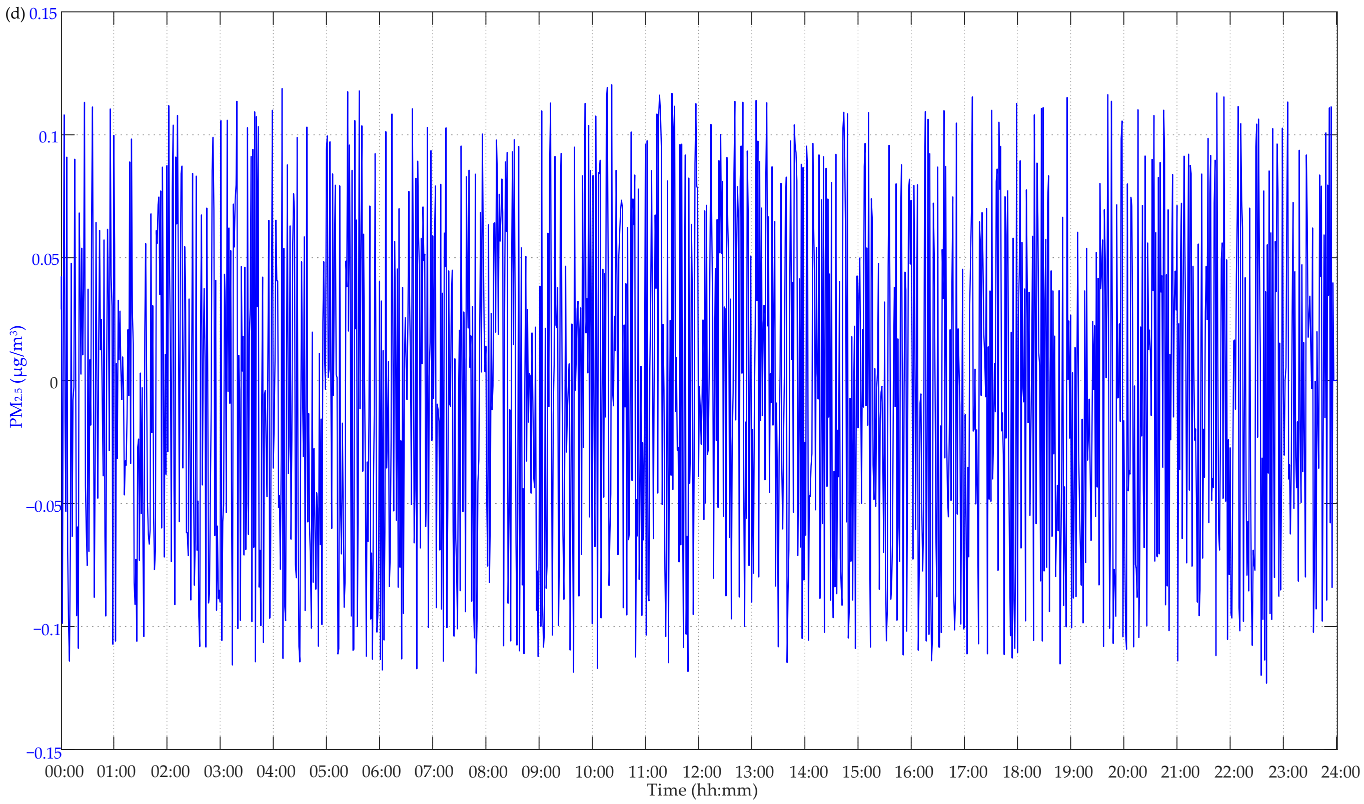


Figure 8. *Cont.*





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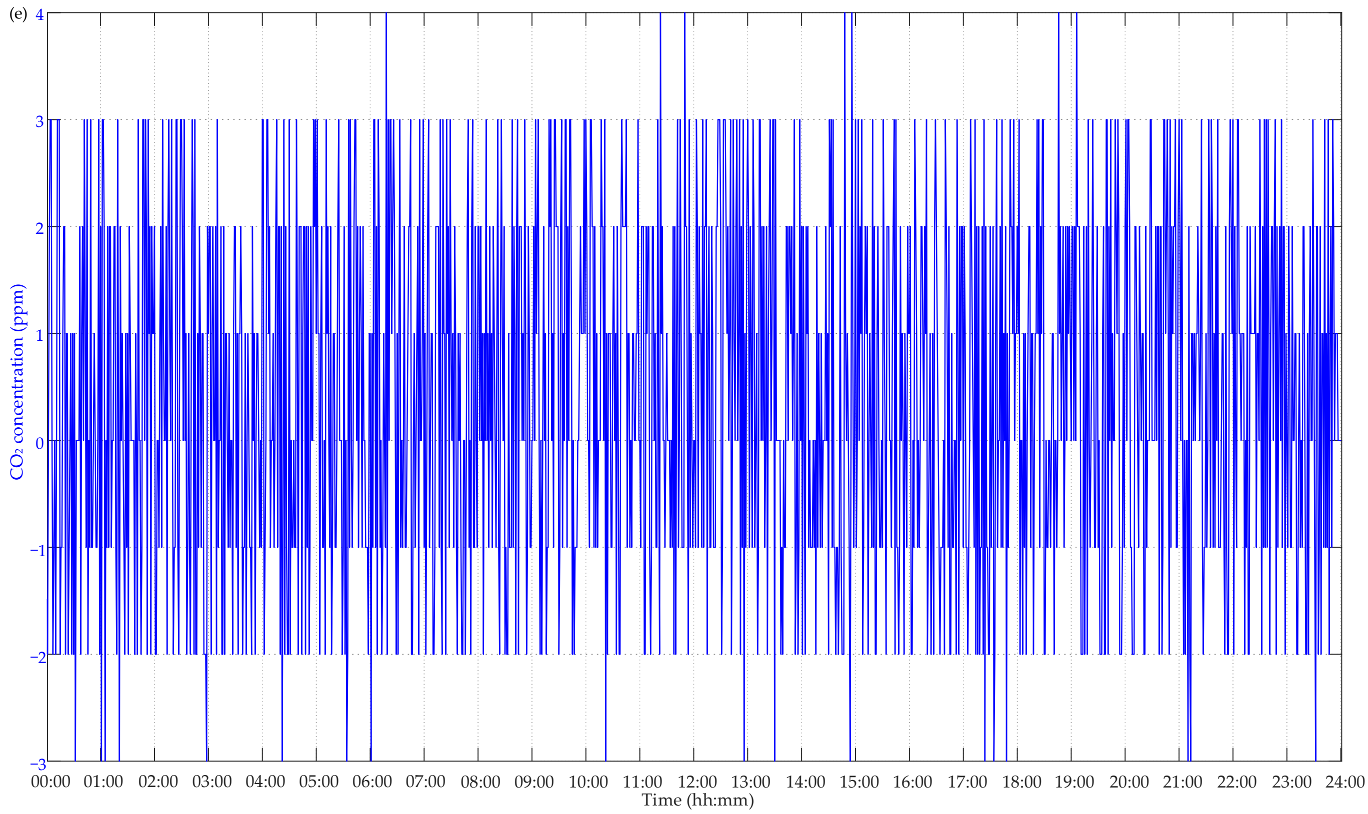

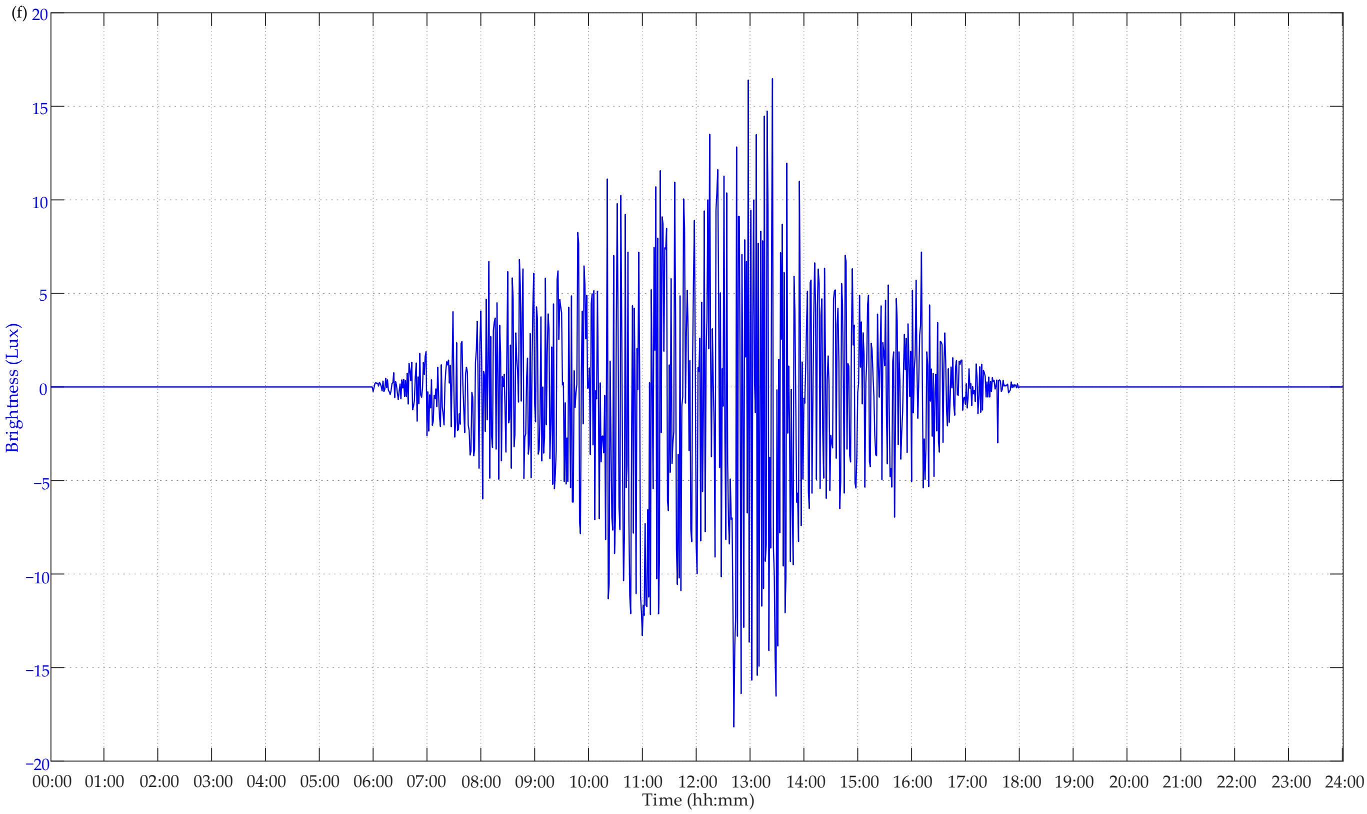

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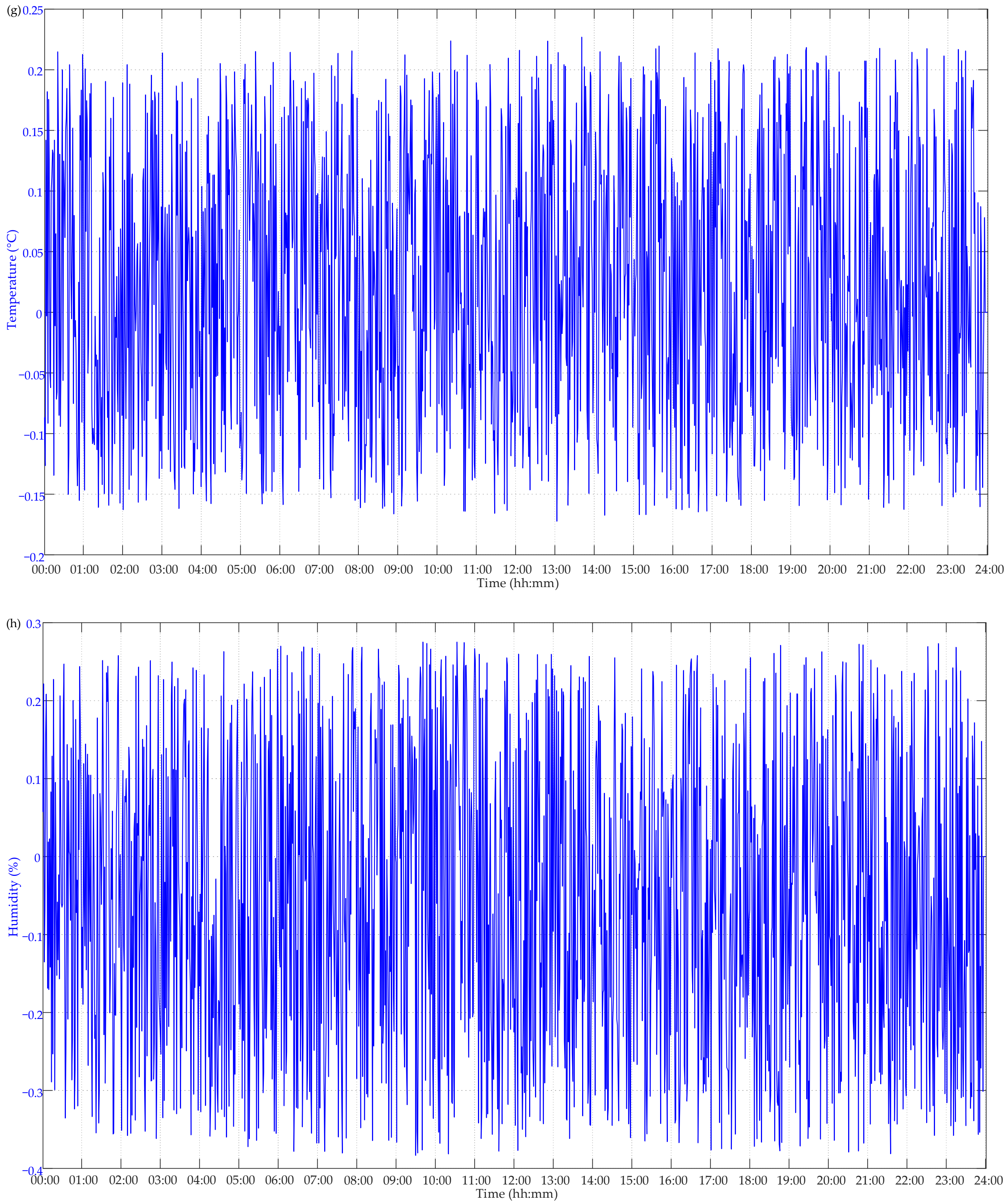

Figure 8. Difference analysis of 24 h in situ measurement results for DYU Air Box compared with corresponding measurement instruments: (**a**) IAQ index; (**b**) IAQ level; (**c**) $PM_{1.0}$ concentration; (**d**) $PM_{2.5}$ concentration; (**e**) CO_2 concentration; (**f**) brightness; (**g**) temperature; (**h**) humidity.

The TES-1337B light intensity meter and TES-1364 temperature/humidity meter were tested. The close-agreement analysis for the proposed DYU Air Box and the corresponding measurement instruments are tabulated in Table 5 in detail. According to the above statistical analyses of measurement results, the MAPE values of the AQI index/level, $PM_{1.0}$ and $PM_{2.5}$ concentrations, CO_2 concentrations, brightness, ambient temperature, and humidity are less than 0.5%, i.e., the sensing accuracy of the DYU Air Box has similarity to the above commercialized measurement instruments of up to 99.5%. The indices of indoor air quality and comfort level including AQI index/level, $PM_{1.0}$ and $PM_{2.5}$ concentrations, CO_2 concentrations as well as brightness, ambient temperature, and humidity can be monitored using the proposed DYU Air Box with sufficient accuracy and confidence that are the same as those of commercialized instruments. The proposed DYU Air Box features the integration of multiple, heterogeneous sensors using I^2C and UART standard communication interfaces.

Table 5. Close-agreement analysis of proposed DYU Air Box and measurement instruments.

Items	Accuracy Analysis			
	Difference Range	**MAE**	**MAPE (%)**	**RMSE**
AQI value	−0.14396–0.1002	0.06	0.31%	0.07
AQI level	0	0	0%	0
$PM_{1.0}$	−0.1157–0.1183 μg/m^3	0.06 μg/m^3	0.37%	0.07 μg/m^3
$PM_{2.5}$	−0.1182–0.11201 μg/m^3	0.06 μg/m^3	0.50%	0.07 μg/m^3
CO_2	−3–4 ppm	1.48 ppm	0.35%	1.72 ppm
Brightness	−15.7741–17.3249 Lux	1.85 Lux	0.25%	3.70 lux
Temperature	−0.1758–0.2280 °C	0.10 °C	0.36%	0.12 °C
Humidity	−0.3894–0.2767%	0.16%	0.31%	0.20%

It should be noted that the surrounding environmental conditions can significantly affect the ones in the H708 classroom from the viewpoint of system dynamics. As shown in Figure 7g, the incoming of solar irradiance increases the brightness which might have a positive effect on learning regarding indoor illumination and food quality. The solar irradiation simultaneously increases the indoor temperature of the classroom and increases the load of air conditioners. Therefore, a curtain shield is necessary for the comfort of classmates during class hours, and this could save the electricity consumption of air conditioners. Furthermore, Figure 7a,h reveal the close correlation between AQI value and humidity; therefore, suitable dehumidification is suggested to keep good indoor air quality. Furthermore, air purifiers can effectively remove $PM_{2.5}$ as shown in Figure 7d. The findings of a mutual effect between AQI value/level and RH, as well as a positive effect of $PM_{2.5}$ purification by HVAC, can be adopted to improve AQI level. It should be noted that HVAC operation has no effect on the $PM_{1.0}$ removal. Therefore, the proposed DYU Air Box and the public ThingSpeak IoT platform for the H708 classroom can monitor the degree of comfort and indoor air quality for students and teachers in the field and the information of the environmental conditions can offer environment traceability for all stakeholders. This significantly generates and promotes the environmental, social, and corporate governance (ESG) value of Da-Yeh University for all organizational stakeholders including employees, customers, suppliers, and financiers.

4. Discussion

The issues of power consumption, easy maintenance, and periodical calibration were taken into consideration in the development stages. First of all, the operating current values of the BME680, PMS7005, SCD30, and BH1750 are 714 μA (maximum for pressure measurement), 100 mA, 19 mA, and 190 μA, respectively. Therefore, the total current and power consumption requirement and power consumption of the sensors are 120 mA and 600 mW, respectively. The built-in power IC in the TTGO ESP32 Wi-Fi module can sufficiently provide 5/3.3 V_{DC} operation voltage, current, and power consumption for itself and the additional sensors. On the other hand, the well-designed 4-pin dip header and socket of 2.54 mm for standard series communication interfaces including the I^2C and UART interfaces provide the customized wireless multi-sensor module much convenience in installation and maintenance of multiple heterogeneous sensors. Based on the PCB design for the standard I^2C extension, additional heterogeneous sensors with a standard I^2C interface can be easily aggregated in the proposed wireless multi-sensor modules. Due to the oxidation/reduction on its sensitive metal-oxide-based layer, the BME680 gas sensor detects and measures AQI for the concentration level of ethanol and b-VOCs, and the periodical calibration of BME680 with an instrument is necessary.

The cost of the proposed wireless multi-sensor module is about USD 58, including TTGO ESP32 Wi-Fi device: USD 20, BH1750: USD 5, BME680: USD 8, PMS7003T: USD 20, and PCB: USD 5. The cost for the commercially available Enviro+ Raspberry Pi HAT is over USD 70 even without taking both the dust sensor and Raspberry Pi platform into account. Furthermore, the price of the Verkada SV11-HW is over USD 1500 online, and an extra fee is necessary for the application platform. Therefore, the proposed wireless DYU Air Box is much more cost-effective as compared to the above two commercialized devices.

5. Conclusions

This paper firstly proposes a wireless DYU Air Box in which a TTGO ESP32 Wi-Fi device was adopted to aggregate heterogeneous devices of a BME680 air quality index (AQI) sensor, PMS7003T $PM_{1.0}/PM_{2.5}$ sensor, SCD30 carbon dioxide (CO_2) sensor, and BH1750 light sensor to acquire the data of AQI value and level, $PM_{1.0}$ and $PM_{2.5}$ concentrations, CO_2 concentration, brightness, ambient temperature, and relative humidity (RH). The acquired data were forwarded to the public ThingSpeak IoT platform through the existing DYU-802.1X Wi-Fi network with Wi-Fi Protected Access 2 (WPA2) Enterprise security based on the Hypertext Transfer Protocol (HTTP). With the help of the existing DYU-802.1X network and the public ThingSpeak IoT platform, the implementation and evaluation of the DYU Air Box for the environment-monitoring IoT system are completely conducted with sufficient accuracy. The acquired data of the DYU Air Box were evaluated with the following commercially available measurement instruments: a TES-1337B light intensity meter, a TES-1364 temperature and humidity meter, a TES-1370H CO_2 meter, a TES-5110 particle counter, and a TES-5322A IAQ meter. The results reveal that the mean absolute percentage error (MAPE) values between the sensing data and the readings of the instruments were less than 0.5% which reveals that the proposed DYU Air Box has a close agreement with the above instruments of over 99.5%. As compared to the two commercialized devices of Enviro+ Raspberry Pi HAT and Verkada SV11-HW, the DYU Air Box is more cost-effective than them. Therefore, the proposed DYU Air Box features cost-effectiveness and sufficient accuracy and confidence. Due to the visualization limits of the public ThingSpeak IoT platform, further work will be aimed to development a private DYU EMIoT system which will allow the observation of multiple DYU Air Box devices through the DYU-802.1X Wi-Fi network with WPA2 Enterprise security on campus. Furthermore, the planned DYU EMIoT system will feature simultaneous observations for the public ThingSpeak IoT platform and a customized, private environment-monitoring IoT one only using the proposed sensing device. This DYU Air Box with the public ThingSpeak IoT platform is the first step to offer organizational environmental, social, and corporate governance (ESG) value for all stakeholders including the students, faculty, and staff on campus as well as other stakeholders such as the alumni and students' parents. Furthermore, both the public ThingSpeak IoT platform and private EMIoT system will provide data on the environmental conditions for all stakeholders according to their interests.

Author Contributions: Conceptualization, L.-M.S. and H.-L.T.; methodology, H.-L.T. and L.-M.S.; software, H.-L.T. and C.-Y.T.; validation, L.-M.S., H.-L.T. and C.-Y.T.; formal analysis, H.-L.T. and C.-Y.T.; investigation, H.-L.T.; writing—original draft preparation, H.-L.T.; visualization, L.-M.S. and C.-Y.T.; supervision, H.-L.T.; project administration, L.-M.S.; funding acquisition, L.-M.S. and H.-L.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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